The End-to-End Model of the Very Large Telescope Interferometer (VLTI)

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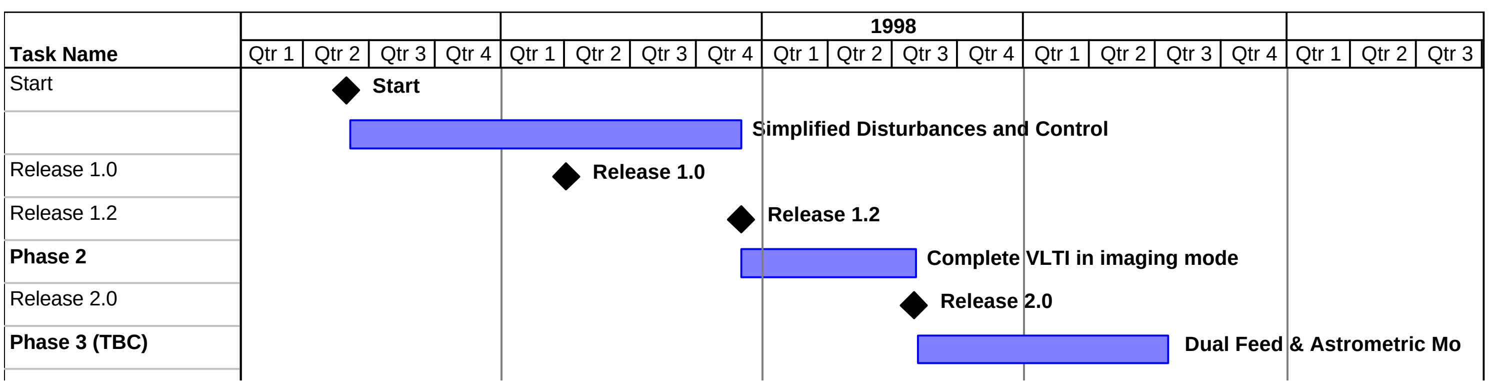
Presentation Overview

- Project overview and objectives
- General Architecture
- Main User Interfaces
- Main Model features
- Highlights of Modeling approach
  - Optics
  - Mechanics
  - Control
  - Disturbances
- Some typical output
- Conclusion

Project overview

- Precursor: The VLT Unit Telescope Model 1994-95
  - contract with Ball Aerospace, Khoros environment
- VLTI Model started in June 1996,
  - developed in-house in MATLAB/Simulink environment
- Resources/cost: ≈1.2 FTE (average) + Matlab licenses
- ⇒ Relatively small project, No attempt to generate a general-purpose tool
- Schedule:



Project Objectives (1/3)

- General Objective:
  - Produce a representation of the main output of the interferometer, i.e. the intensity produced by the superposition of the EM fields collected in
    - a pupil plane, or
    - an image plane,
    - along a single line of site
- Rationale:
  - Support Design & System Enginnering activities
  - Provide simulated output of the interferometer for a Science Model
  - Provide a diagnosis tool during the Commissioning of the Interferometer

Project Objectives (2/3)

- Engineering objectives:
  - Analyse collective effects of disturbances
    - in the time domain instead of Spectrum + quadratic sum
  - Analyse interaction of optics & control loops
    - including cross-coupling between Fringe/Image/Pupil tracking
  - Validate & maintain the main VLTI error budgets
  - Study design alternatives when necessary and when having high impact at system level (e.g. UT Coudé Train, Dual Feed mode, etc.)
  - Complement to CODEV for specific optical analysis (e.g. global sensitivity analysis,...)
  - Provide representative simulated data to the Instrument Teams for instruments design
  - By-product: building the model can improve the understanding of "how the system works"

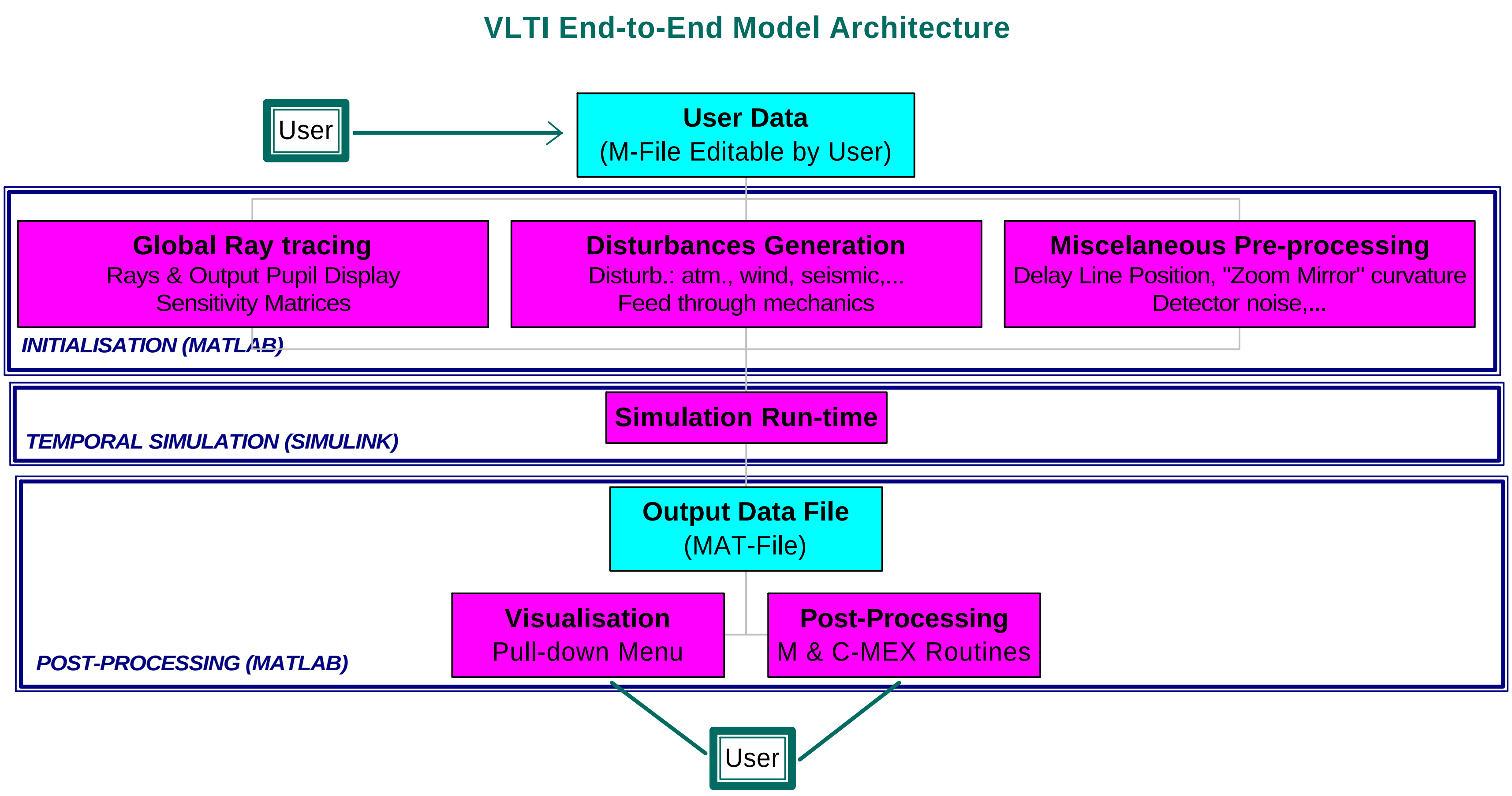
Project Objectives (3/3)

- Science Model (separate project):
  - Objective: provide simulated data as coming out from the instruments including:
    - » Detailed model of astronomical source
    - » Array configuration
    - » Detailed Instrument model
    - » Background, Detector & Photon Noise

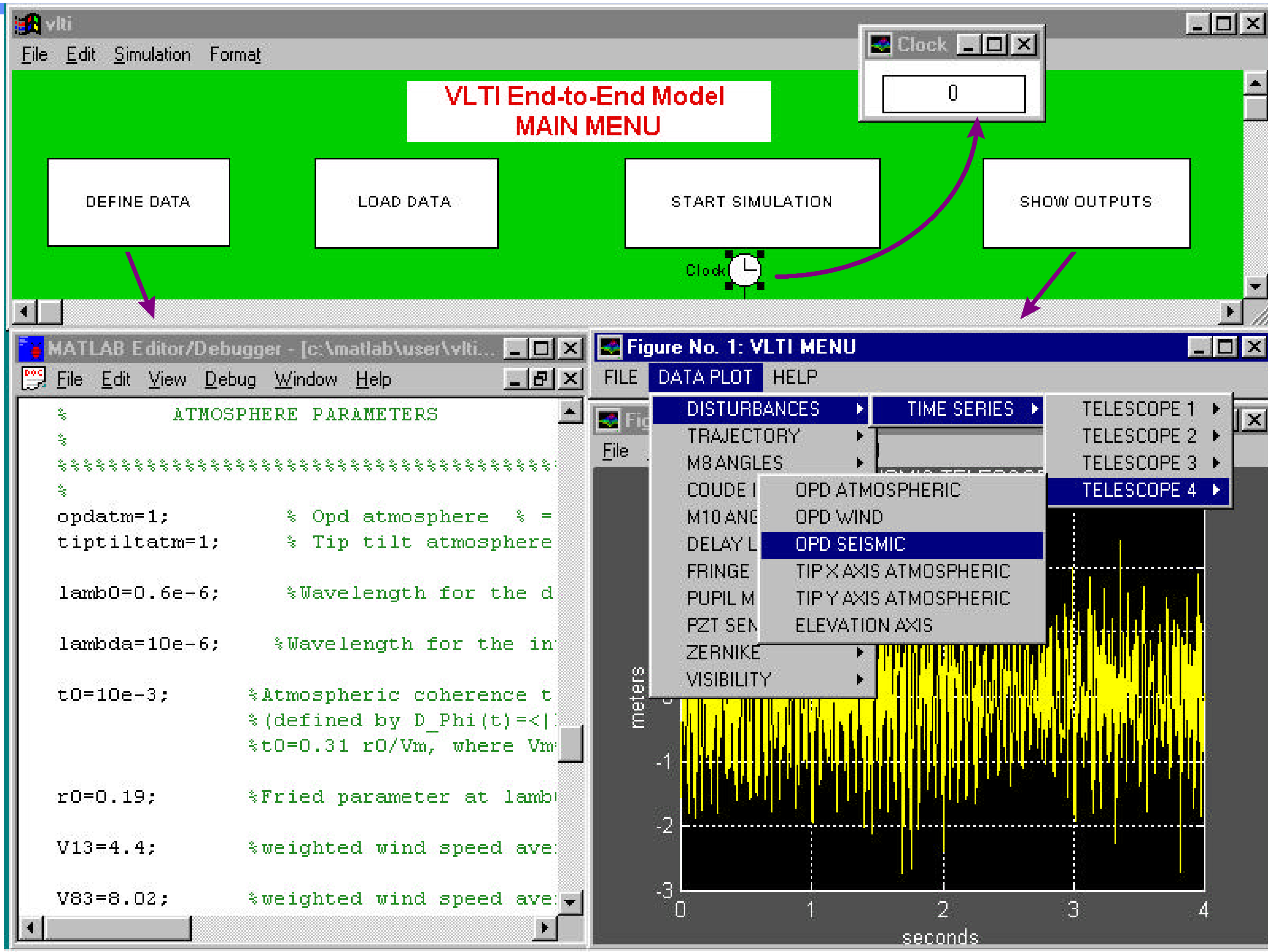
    in order to assess the final Science Performance
  - Use the output from the Technical Model as input data
  - UNIX, C++, Tcl/Tk
  - 1 FTE (M. Schöller) since July 1997
- Diagnosis tool during the Commissioning
  - Can help understand problems observed
  - Check impact of possible modifications/improvement

General Architecture

- MATLAB 5.1 / SIMULINK 2.1 Environment for PC



Main User Interfaces



Main Model Features (1/3)

- Modeling features

Optics	Mechanics	Control
Build-in Ray Tracing Mirrors: flat, cylinder, sphere, conic	Linear models Frequency Response (FR) or State Space representation (SS)	Full Simulink capabilities
"Perfect" surfaces Prescription errors but no figuring errors	FR or SS computed before-hand by FEM, and loaded from file	Linear detector models frequency resp. and noise
5 DOF's / mirror X, Y, Z, α, ß	Direct interface with FEM	Linear control laws
Figuring errors	Built-in Finite Element capabilities	Complete Detector models
Photometry		Mode Switching
Polarization		
Full Diffraction		
Dispersion		

Legend: Version 1 (done) Version 2 (in progress) Version 3 (TBC)

Main Model Features (2/3)

- Physical features

Object	VLTI Sub-systems	Disturbances
Point Source With associated Magnitude & Visibility (for Detectors)	4 Telescopes among 4 UT and 30 AT stations	Atmosphere - Piston, - Tip/Tilt
Monochromatic	4 Delay Lines among 8 available Delay Lines incl. Variable Curvature Mirror	Wind load on Tel. - Piston, - Tip/Tilt
Diurnal motion	Idealized Instrument Pupil & Image plane	Seismic - Piston
Polychromatic	Main Control Loops - Fast Tip/Tilt, - Lateral Pupil Position, - Fringe Tracking	Atmosphere - Wave Front Error
	Adaptive Optics	Internal Seeing
	Dual Feed mode	
Extended Object	"Real" Instruments	

Legend: Version 1 (done) Version 2 (in progress) Version 3 (TBC)

Main Model Features (3/3)

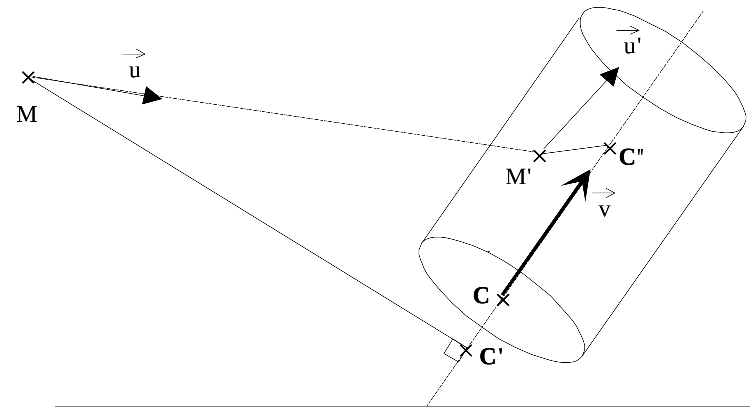
- User Interface features

Output parameters	Post-processing	GUI
Computed in User-defined output plane	Plot of individual variables	Limited: Input: Edit M-File Run: Simulink GUI Ouput: Pull-down menu
For each beam: - Chief-Ray position, X, Y, Z - Chief-Ray OPL - Pupil Position X, Y, Z - Phase Map (Zernike) - Image pos. at Tel.. coudé - Pupil diameters	Spot diagrams, PSF, Phase Map	
	Visibility v. Time	
	Combined Image Map	
	Combined Pupil Map	

Legend: Version 1 (done) Version 2 (in progress) Version 3 (TBC)

Highlights of Modeling Approach

- Optics Modeling
  - Ray tracing using analytical formulae
  - Sensitivity matrices computed during initialisation by modifying each Degree of Freedom
  - Output:
    - Chief ray position,
    - Optical Path Length of Chief Ray
    - Ouptut Pupil position
    - Phase map projected on Zernike modes
    - Additional parameters required by Control Loop (e.g. Image pos. at Coudé Focus



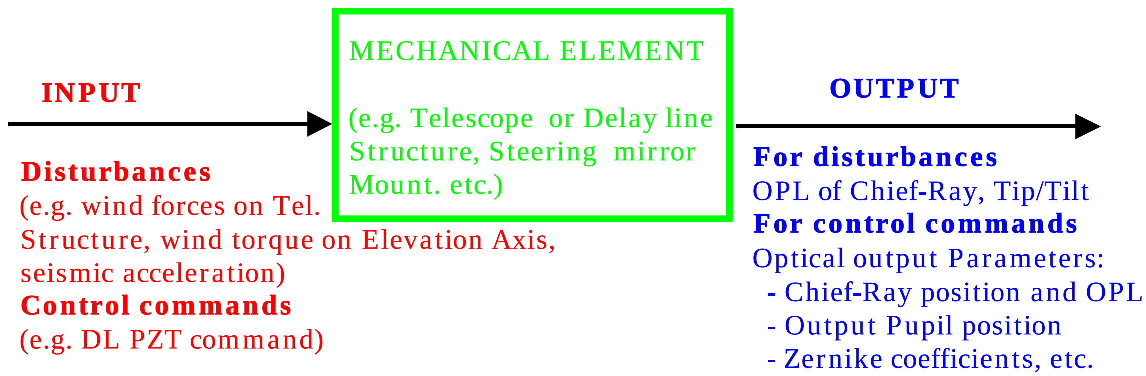
The equations giving M', $\vec{u}'$, and $\vec{n}'$ are therefore:

$$\begin{cases} a = 1 - (\vec{u}\cdot\vec{v})^2 \\ b = 2.\left[(\vec{u}\cdot\vec{v})\cdot(\mathbf{MC}\cdot\vec{v}) - \mathbf{MC}\cdot\vec{u}\right] \\ c = \mathbf{MC}\cdot\mathbf{MC} - (\mathbf{MC}\cdot\vec{v})^2 - R^2 \\ \Delta = b^2 - 4.a.c \\ d = \dfrac{-b + flag.\sqrt{\Delta}}{2.a} \\ M' = M + d.\vec{u} \\ \vec{n}' = -flag \times \dfrac{(\mathbf{MC}\cdot\vec{v})\cdot\vec{v} - \mathbf{MC} + d.\left[\vec{u} - (\vec{u}\cdot\vec{v})\cdot\vec{v}\right]}{R} \\ \vec{u}' = \vec{u} - 2(\vec{u}\cdot\vec{n}')\cdot\vec{n}' \end{cases}$$

$$\text{where} \begin{cases} flag = +1 \text{ If mirror is CONCAVE} \\ flag = -1 \text{ If mirror is CONVEX} \end{cases}$$

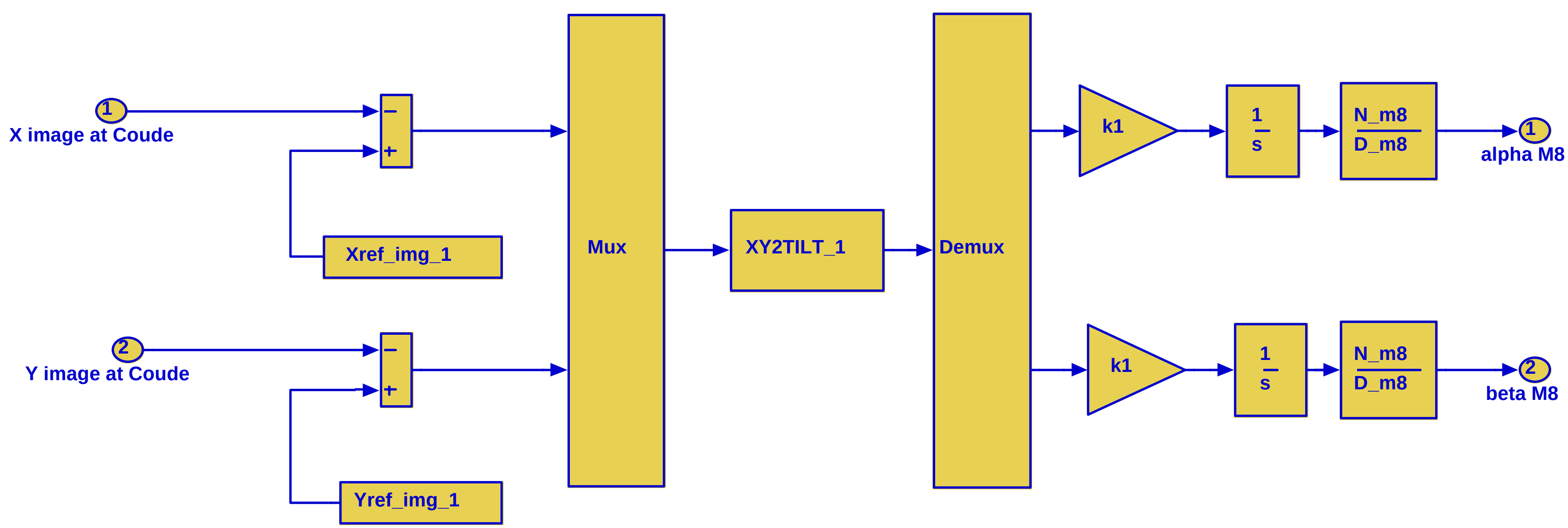
Highlights of Modeling Approach

- Mechanics Modeling
  - For Disturbance effects: Linear models based on Transfer Functions Computed from FEM
    - » All modes included in numerical representation: $[f_i, TF(f_i)]$, $i=1\ldots N$, f_i log spaced
  - For Control loops: State Space Representation, [Num,Den] or [a,b,c,d]
    - » Need model reduction
  - All FEM computations done off-line (ANSYS)



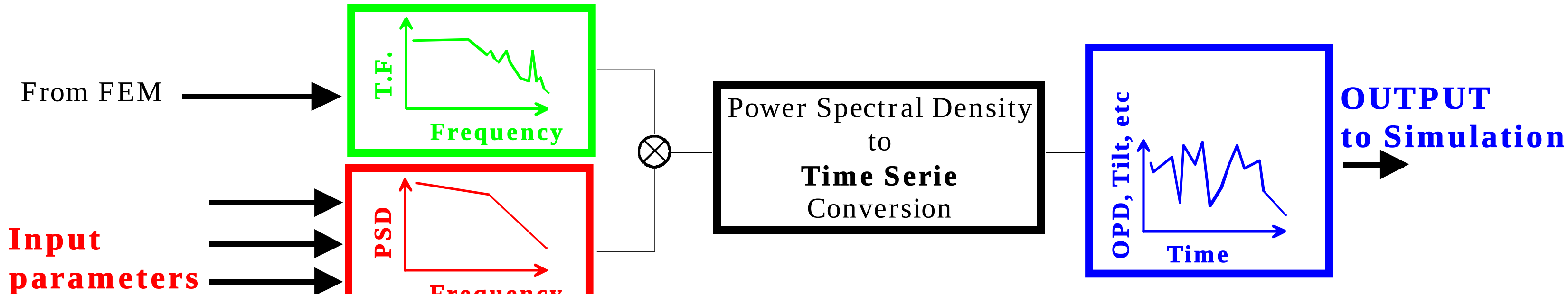
Highlights of Modeling Approach

- Control loop Modeling
  - Full use of Simulink capabilities
  - Pre-processing of data during Initialisation (e.g. Gain setting, Sensor noise versus star magnitude, etc.)



Highlights of Modeling Approach

- Disturbances Modeling
  - Uses Analytical expressions of Power Spectral Densities (PSD) of Disturbance (wind speed, Atmospheric piston & G-tilt) or measured data (seimic acceleration).
  - Multiply by appropriate mechanical Transfer Function (TF)
  - Generate random time series of optical parameters: OPL, Tip/Tilt,...



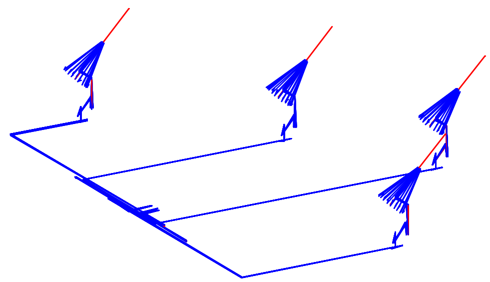
Wind: U, I, L, A

Atmosphere: $r_0, \tau_0, \lambda, V_{-1/3}, V_{8/3}$

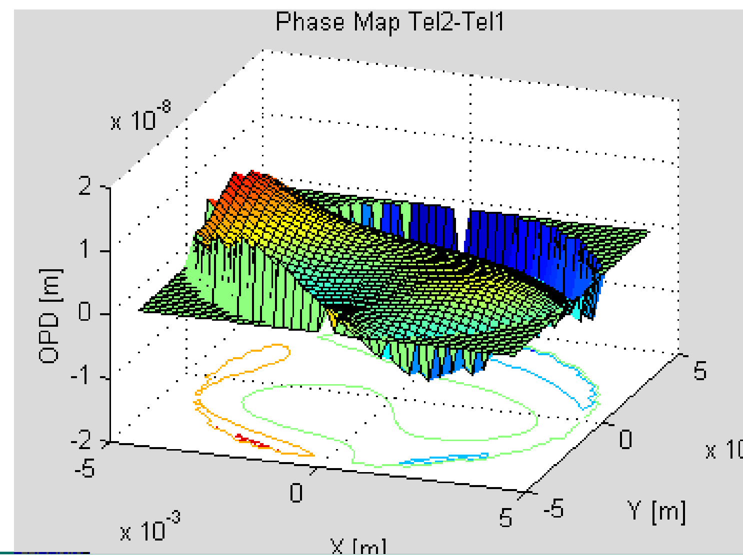
Seismic: measurement file name

Some typical Output (1/2)

- Ray tracing plots
  - 2-D & 3-D views
  - Zoom capability
  - plot of pupil rays to locate pupil

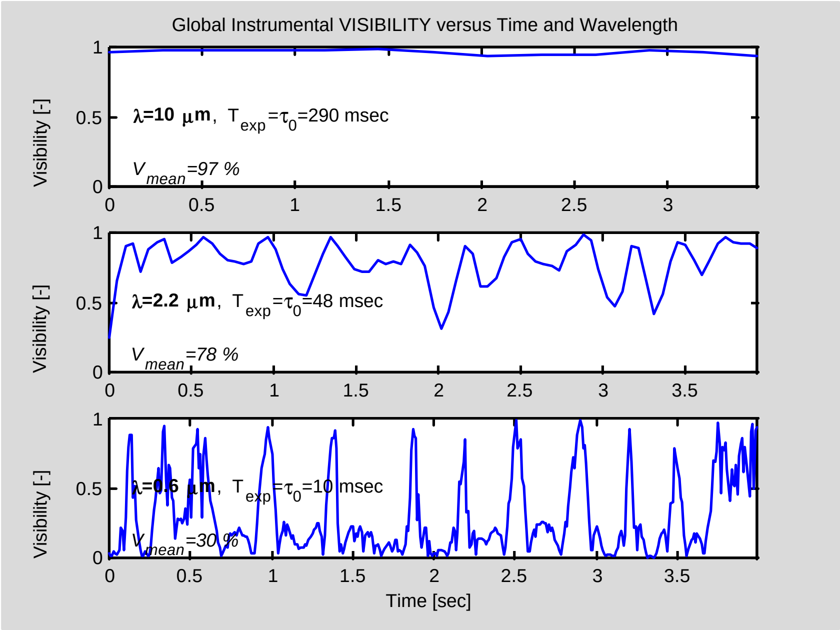


- Phase Maps
  - For each beam or differential between two telescopes
  - Static or movie versus time
  - Selection of particular zernike modes



Some typical Output (2/2)

- Visibility versus time



- Plus more under development...
  - Combined pupil intensity
  - Combined image intensity
  - Combined image movie, etc.

Conclusion

- Status:
  - Version 1.2 (complete optical train, simplified disturbances and control)
    available
  - Version 2 (complete and detailed disturbances and control)
    under development
- Outcome to date:
  - Global optical sensitivity matrices
  - Trade-offs on UT Coudé Train design
  - Fluctuation of visibility versus time (calibration issue), and more...
- Next steps
  - More analysis with Version 1.2 and 2
  - Version 3 (Dual Feed, Astrometric Mode, “actual” instruments)
    to be defined